Space Interferometry Mission: Dim Starlight Information Processing

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Abstract

We present an overview of Space Interferometry Mission with a particular attention to its metrology subsystem. With SIM, the space-based optical interferometer is designed to measure star distances with microarcsecond resolution, which would be about two orders of magnitude improvement over what is presently available. In order to achieve the microarcsecond astrometry, a metrology system capable of measuring picometer resolution is required. After describing the overall concept of SIM, we will describe our approach to the picometer metrology and the progress that has been made to date.

S I M

Space
Interferometry
Mission

Space Interferometry Mission: Picometer Metrology for Microarcsecond Astrometry

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SIM

Space Interferometry Mission

Outline

- Overview of Space Interferometry Mission (SIM)
  - Astrometry using Interferometry
  - How SIM does Astrometry, Imaging, and Nulling
  - SIM Science
  - The SIM architecture
- Picometer Metrology Subsystem
  - What metrology subsystem measures
  - Components of metrology subsystem
  - SAM and FAM
  - Challenging issues
- How to obtain more information about SIM

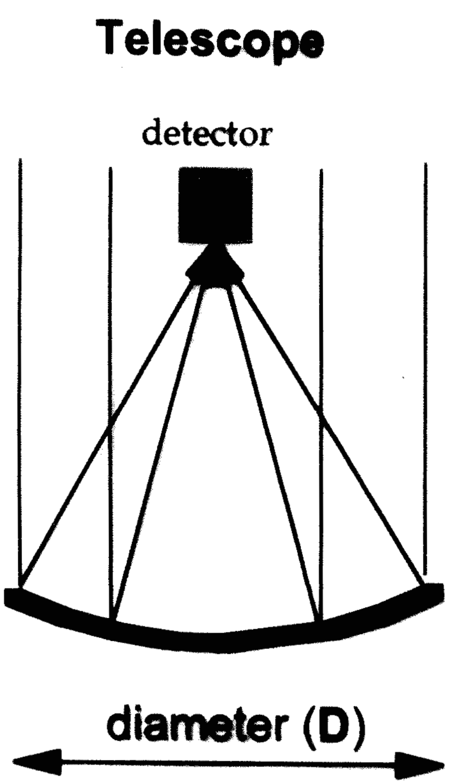
SIM

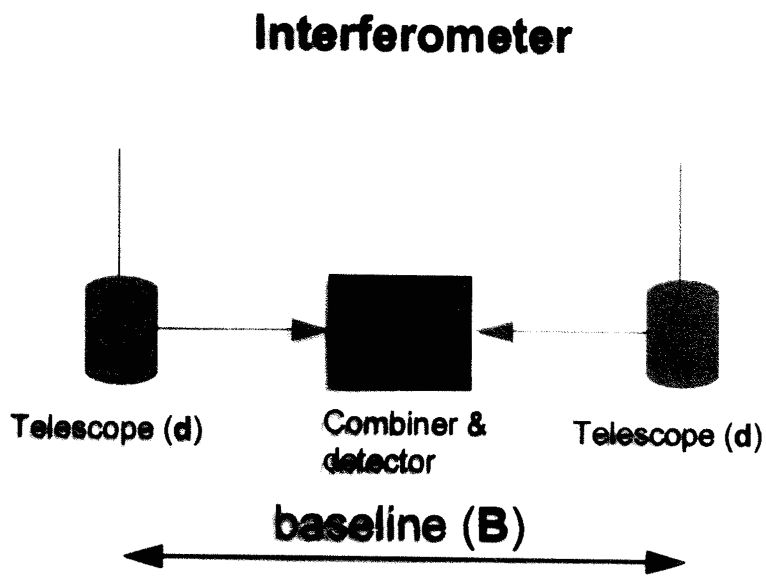
SPACE INTERFEROMETRY MISSION

Interferometers vs. Telescopes

- *An interferometer provides a potentially less expensive way to achieve very high resolution*

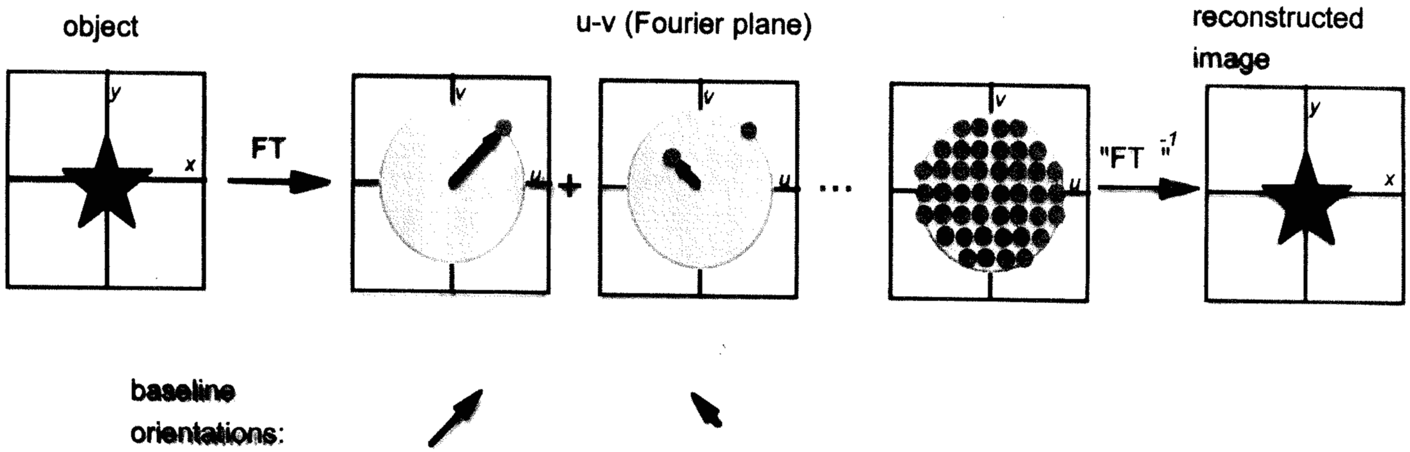
	Resolution	Sensitivity
Telescope	λ/D	∝D
Interferometer	λ/B	∝√(2*d*B)





SIM

Imaging with SIM



- *The interferometer measures the Fourier transform of the object.*
- *Each baseline orientation selects one point in the (u,v) plane.*
- *With many baseline orientations and lengths, you fill in the (u,v) plane.*
- *The image is reconstructed from these Fourier-domain measurements.*

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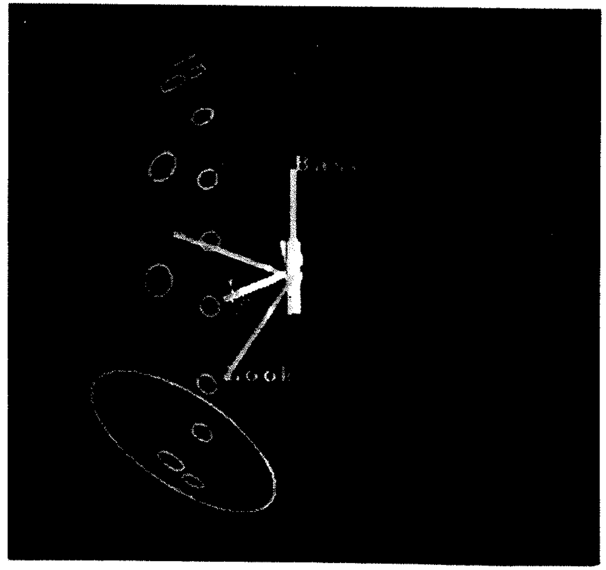
SIM

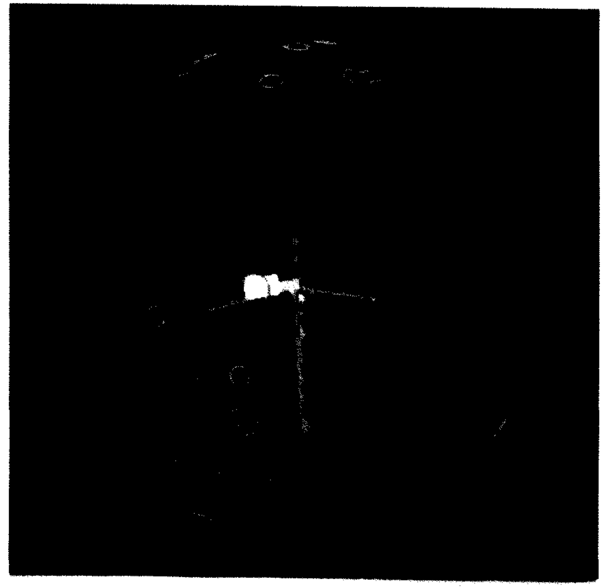
SIM Top-Level Requirements and Implications on Design

Item	Requirements	Implications
Architecture	Optical Interferometer	SIM Architecture
Astrometric Field of Regard	7.5° Conical half-angle	Sets range of compressor articulation
Astrometric Accuracy	4 μas wide angle, 1 μas narrow angle	Sets accuracy of laser metrology system
Astrometric Sensitivity	Targets to 20th magnitude	Sets product of baseline and aperture diameter
Imaging Resolution	10 mas	Sets baseline ≥ 10 m
Imaging Capability	400 (u,v) points	Requires variable baseline lengths, orientations
Interferometric nulling	Null depth ≥ 10	Requires nulling combiner, strict pathlength control

SIM Grid Campagn Sky Coverage

- Sky Coverage in Dedicated Grid Campaigns by "Orange Peel" Scan-Law
  - Systematic "Brick-Work" Coverage of Available Sky Using Anti-Sun as Symmetry Axis
- Evaluating Anti-Sun Exclusion Zone





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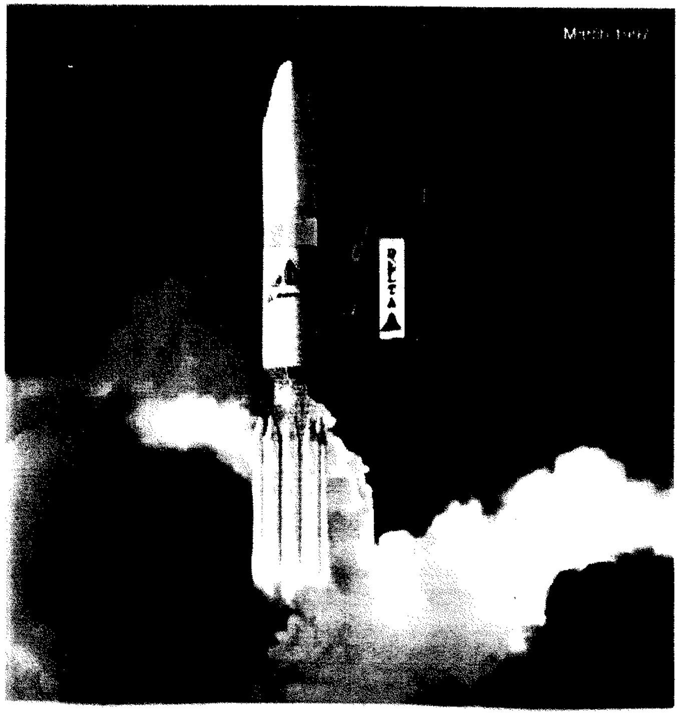
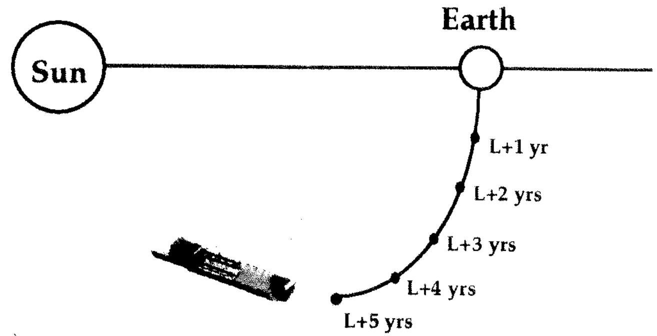
SIM

Orbit and Launch Vehicle

Delta III



Earth-Trailing Solar Orbit



C3:	0.4 Km^2/Sec^2
Occultations:	None
5-yr Radiation Dose:	20 Krads
Launch Vehicle:	Delta III or EELV
Orbit Determination:	Range/Doppler
Earth-S/C Range:	Up to 95 Million Km
Launch Period:	June, 2005
Mission Duration:	5 Years

SPACE
INTERFEROMETRY
MISSION

SIM

SIM science summary

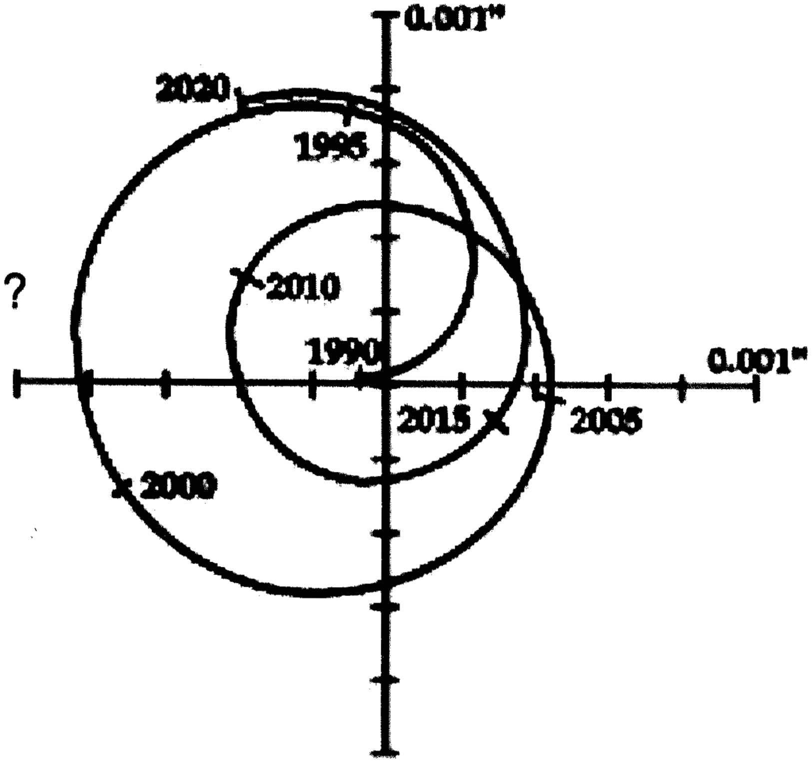
- Search for astrometric signature of planets around nearby stars
- Accurate masses for low-mass binary stars
- Ages of globular clusters
- Calibration of the cosmic distance 'ladder'
- Internal dynamics of globular clusters and dwarf spheroidal galaxies
- Spiral structure of our Galaxy
- Mass distribution in the halo of our Galaxy
- Dynamics of our Local Group of galaxies
- Imaging of emission-line gas around black holes in active galactic nuclei
- Proper motions of active galactic nuclei
- Detection of dust disks around nearby stars
- Distances to spiral galaxies using rotational parallaxes

Searching for planets around other stars

S I M

Space Interferometry Mission

- Questions:
  - > Are planets around other stars common?
  - > Are certain spectral types favored?
  - > What is the mass distribution of planets?
- Method: astrometric detection of 'wobble' due to gravitational tug of unseen planets
- Jupiter-mass planets - signature is ± 5 μas at 1 kpc
  - > very large number of targets
- Earth-mass planets - signature is 1650 times smaller (± 0.3 μas at 10 pc)
  - > detectable only around the nearest stars



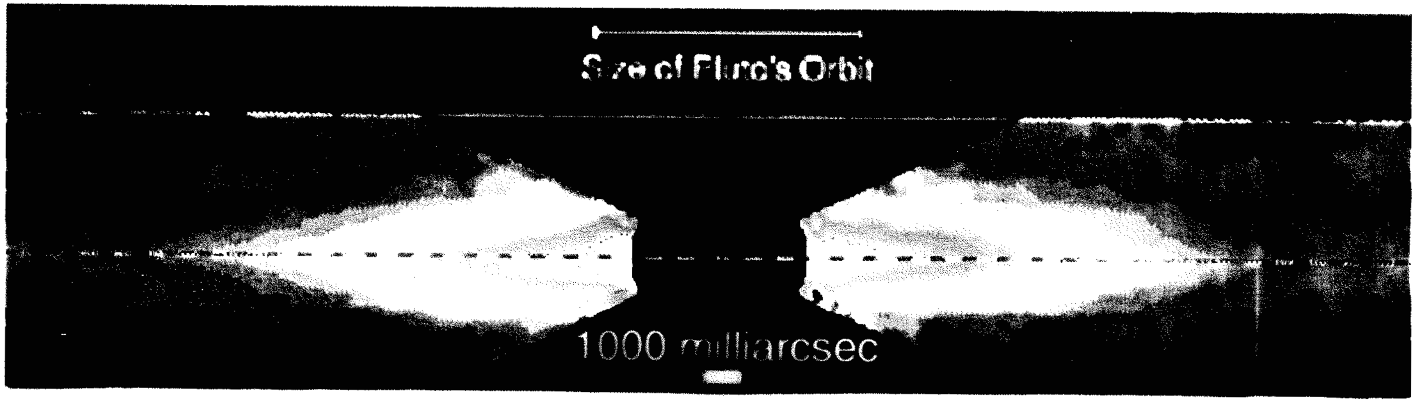
'Wobble' of the solar system as seen from 10 pc away
(" 1000 μas)

Calibration of luminosity and distance indicators in the universe

- Parallax distances to universal 'standard candles'
  - > Cepheids, RR Lyrae Stars, central stars of planetary nebulae

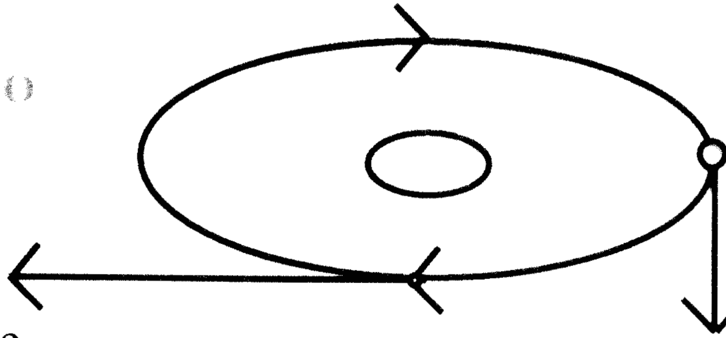
- Ages of globular clusters
  - > Resolve conflict with universe age from Hubble expansion
  - > Calibrate luminosity of main sequence turnoff in metal-poor globular clusters to 1%, by measuring cluster distance, and distances to calibration stars (RR Lyrae stars, field subdwarfs)

- Distances to supernovae in external galaxies
- 'Single-step' measurement, out to ~15 Mpc
  - > Supernovae are extremely bright - detectable to large distances
  - > Measure angular diameter of shell using nulling, to 10^{-4}
    - > Repeat observations to determine *angular* expansion speed
  - > Ground-based spectroscopy to get *radial* expansion velocity
  - > Distance is the ratio of these measurements



- Beta Pictoris: spectral type A5V, V = 3.8, distance = 18 pc
  - > HST / WFPC2 image shows inner 10 arcsec (160 AU) of the dust disk
  - > Disk known to extend to 1000 AU from the star
  - > This disk is atypical. Solar system zodiacal light is $\sim 10^4$ times fainter
  - > Is the dust disk left over after planets have formed?
- SIM will observe dust disks (like Beta Pic) using nulling
  - > Instrument acts like a coronograph
    - > Suppresses central star to $\sim 10^{-4}$ (reduce photon noise from star)
  - > Detect dust within ~0.2 AU of central star (at 18pc)
  - > Is there a 'gap' in the disk, or is it consistent with dust seen further out?

Measuring distances to spiral galaxies using rotational parallaxes



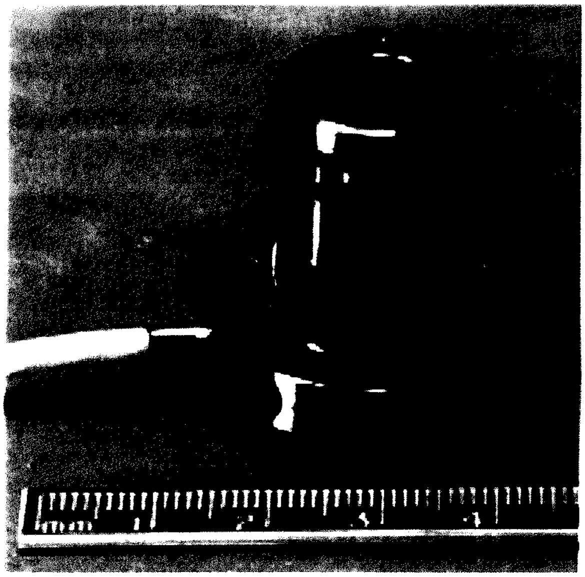
Transverse velocity = $V_{rot} = \mu_{rot} D$

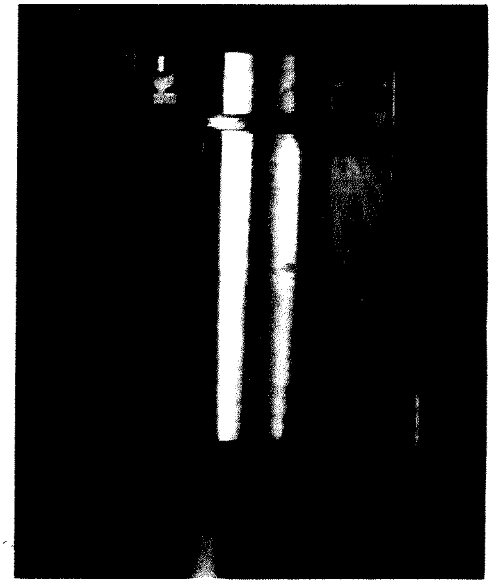
Radial velocity = $V_{rot} \sin i$
Transverse velocity = $V_{rot} \cos i$

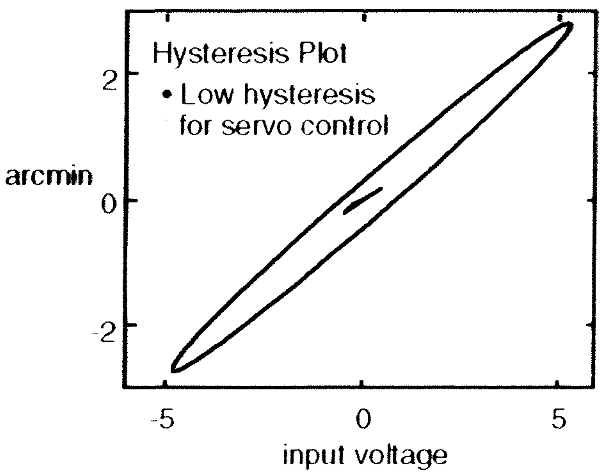
- Measure distance to a galaxy in units of meters
  - > 'Single-step' measurement
  - > Accuracy ~5 % for disk galaxies out to ~ 5 Mpc
  - > Calibration of luminosity vs. peak rotational velocity
    - > Hence accurate distances for very distant galaxies

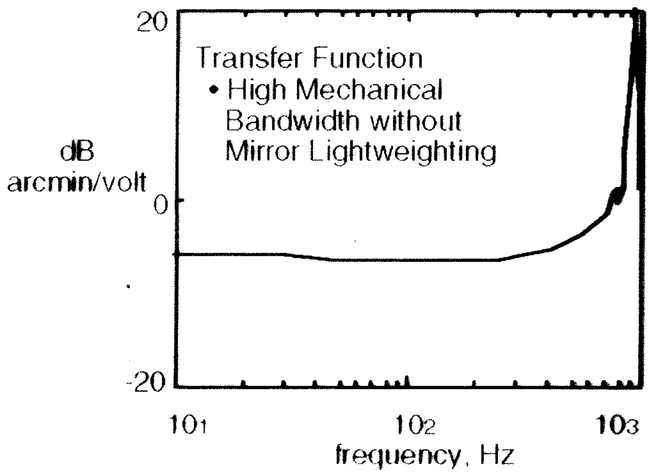
- Method: Astrometric measurement of galactic rotation
  - > Example: M31 at 770 kpc. Rotational velocity (almost flat rotation curve) 250 km/s ⇒ 40 μsec/yr
  - > Select ~25 A-F supergiant stars along major and minor axes
  - > Measure proper motions using SIM
  - > Obtain radial velocities spectroscopically, solve for distance

ARTICULATED MIRROR MECHANISM









Design Requirements

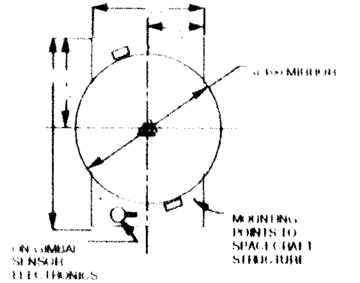
- ± 180 arcmin range
- 600 Hz bandwidth
- stability: 2 arcsec over 24 hrs; jitter: 0.1 arcsec

Design Status

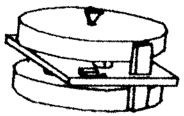
- FSM passed vibration and thermal tests 12/95
- units to be tested and delivered by 9/97
- 0.3 kg (plus 0.15 kg mirror), 5 W

STARLIGHT OPTO-MECHANICAL SUBSYSTEM COMPONENTS

SIDEROSTAT GIMBAL



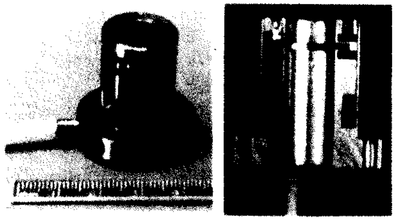
Design Layout for Industry RFP

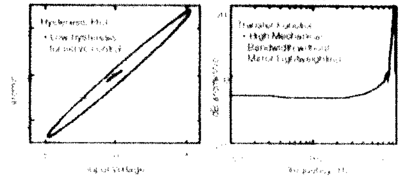


Design Requirements
- ± 2.5 deg range in two axes
- 2 Hz bandwidth
- 0.02 arcsec accuracy and jitter over 10 sec

Design Status
- RFP in progress for brassboard gimbals
- 7.5 kg, 8 W peak
- industry RFI completed

ARTICULATED MIRROR MECHANISM





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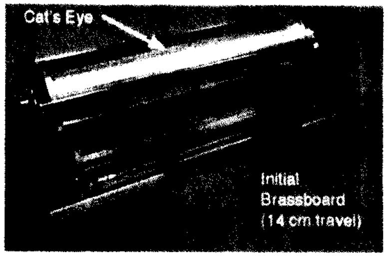
OPTICAL DELAY LINE



Design Requirements
- 100 cm travel
- < 1 nm jitter closed loop
- 1000 Hz closed loop bandwidth
- 3 cm beam, f/5 optic

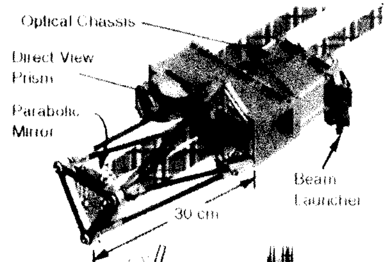
Design Status
- initial brassboard passed vibration and thermal/vacuum tests 12/95
- brassboard with 100 cm travel to be tested and delivered by 12/96
- 16 kg, 10 W

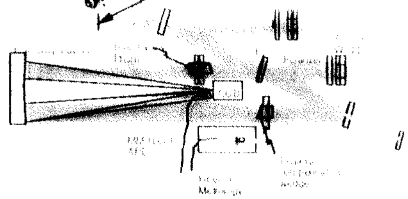
ADJUSTABLE MIRROR CELL

Design Requirements
- 1 arcsec alignment stability
- ± 1 degree range, two axes
- pinned flexure stage
- holds 35 mm optic

Design Status
- < 0.2 arcsec stability after random vibration test 4/96
- 0.2 arcsec adjustment resolution
- design integrated into beam combiner
- 30 grams

ASTROMETRIC BEAM COMBINER

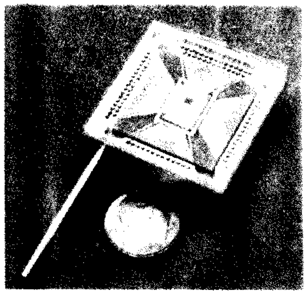




Design Requirements
- perform fringe and fast steering detection
- beam diameter of 30 mm
- optical bandwidth 0.5 to 0.9 microns

Design Status
- brassboard design in progress
- units to be tested and delivered by 1/97
- 7 kg, 10 W

DETECTORS

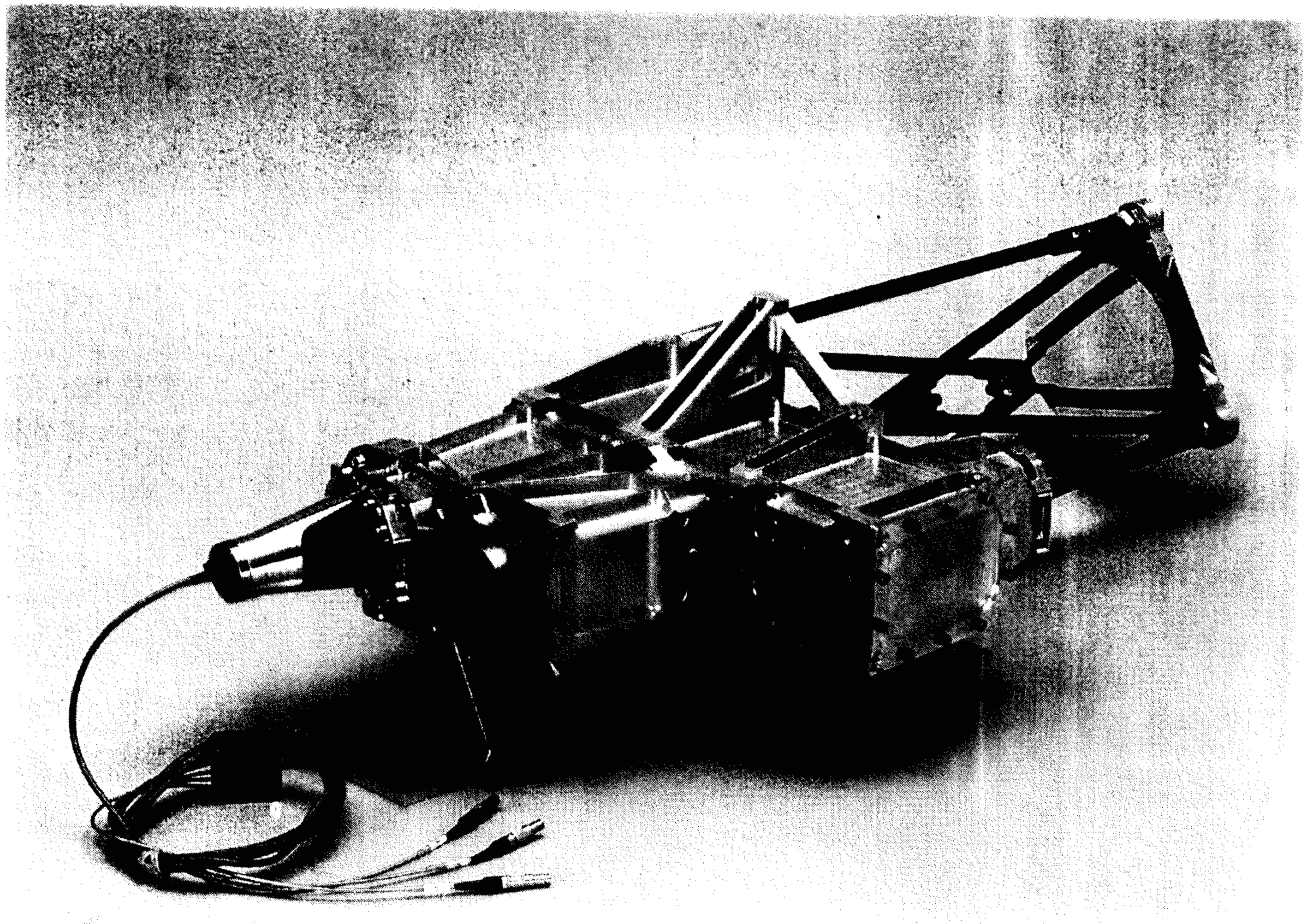


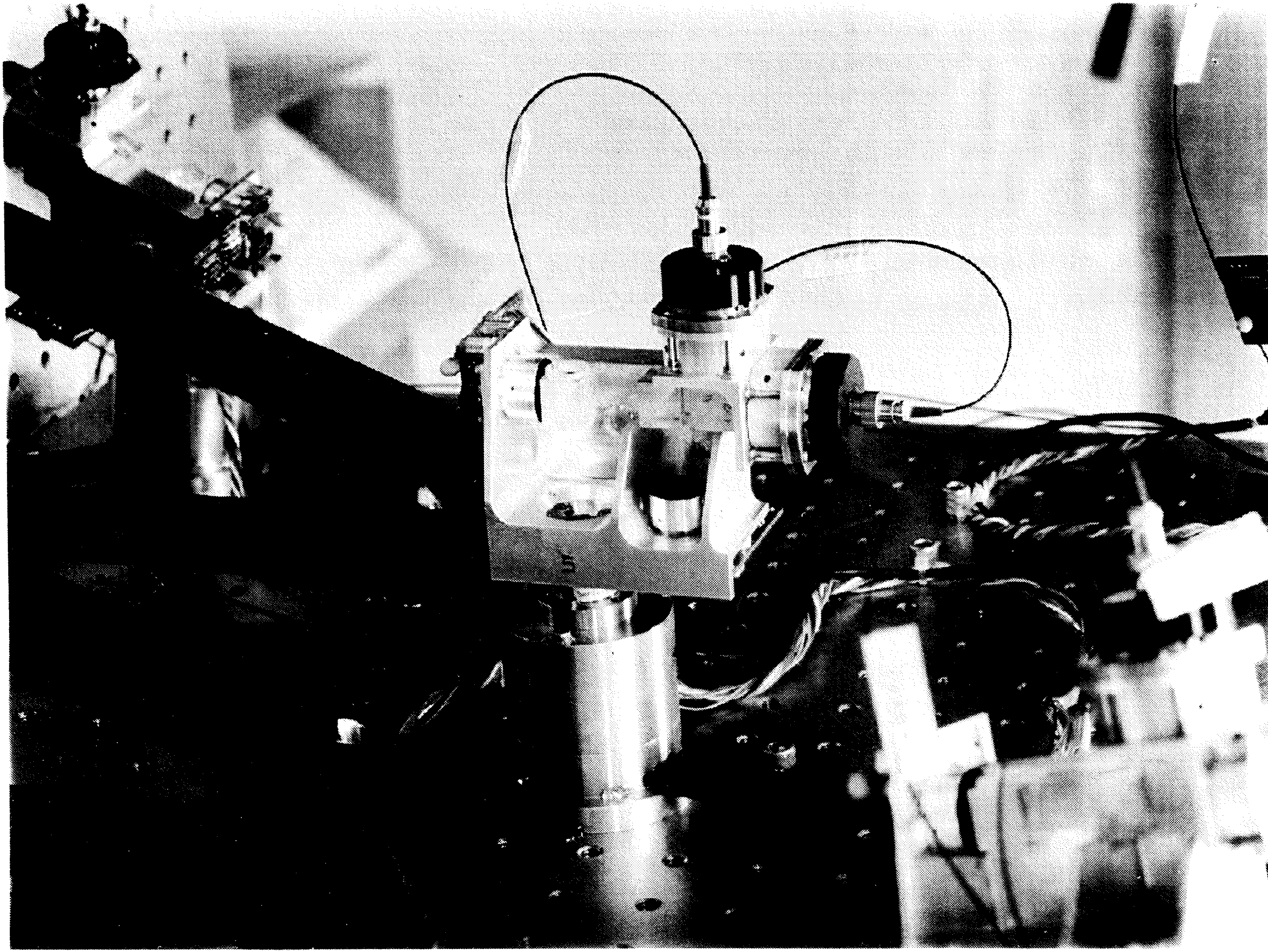
Adapt-2 CCD Chip

Design Requirements
- format: 64x64 frame transfer
- pixel size: 36 micron
- frame rate of 14,500 frames/sec
- gain of 3 microvolts per electron
- noise of 5 e for a single read

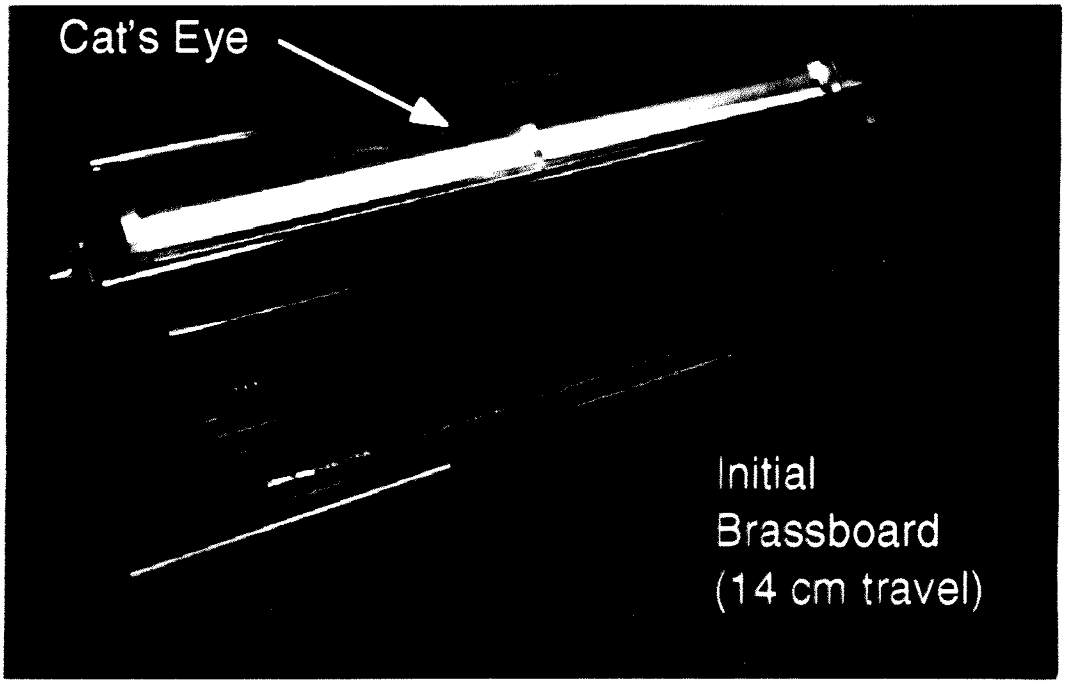
Design Status
- Adapt-2 CCD chips being evaluated for use
- use for ground science FY96
- brassboard design requirements planned for FY97

SIM Beam Combiner





OPTICAL DELAY LINE



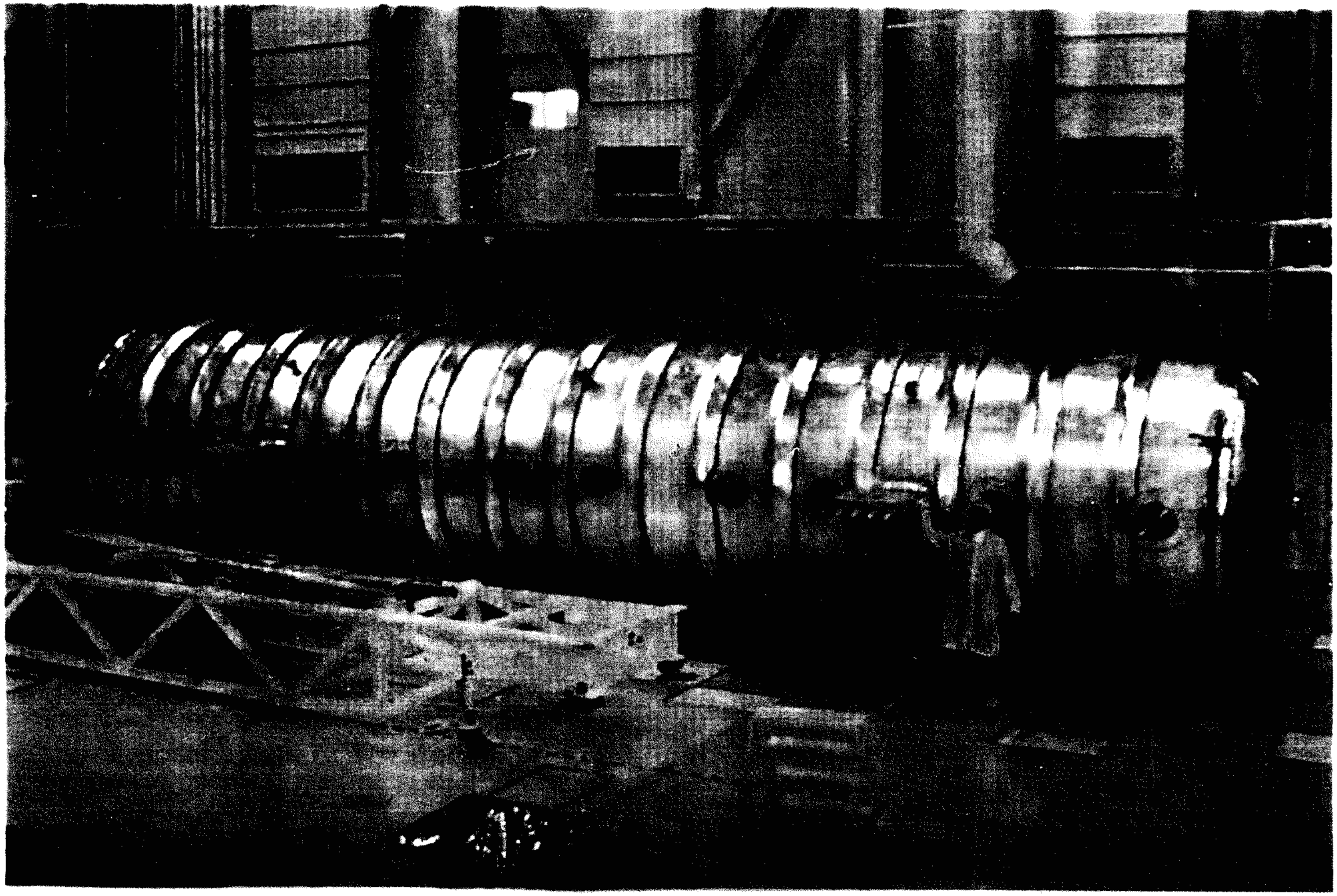
Design Requirements

- 100 cm travel
- < 1 nm jitter closed loop
- 1000 Hz closed loop bandwidth
- 3 cm beam, f/5 optic

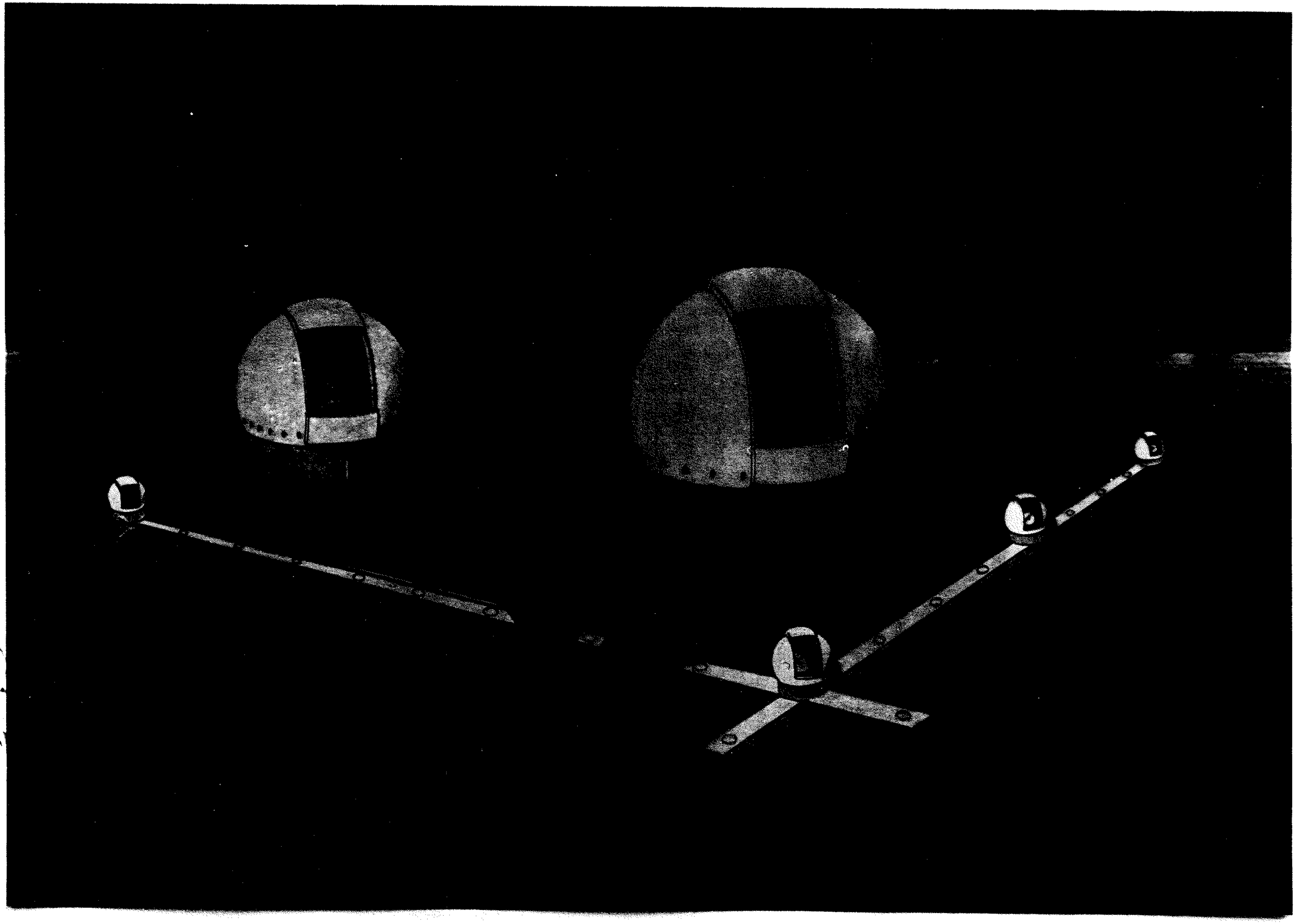
Design Status

- initial brassboard passed vibration and thermal/vacuum tests 12/95
- brassboard with 100 cm travel to be tested and delivered by 12/96
- 16 kg, 10 W

MAM Vacuum Tank 3/12/98
JPL SAF High-Bay 1

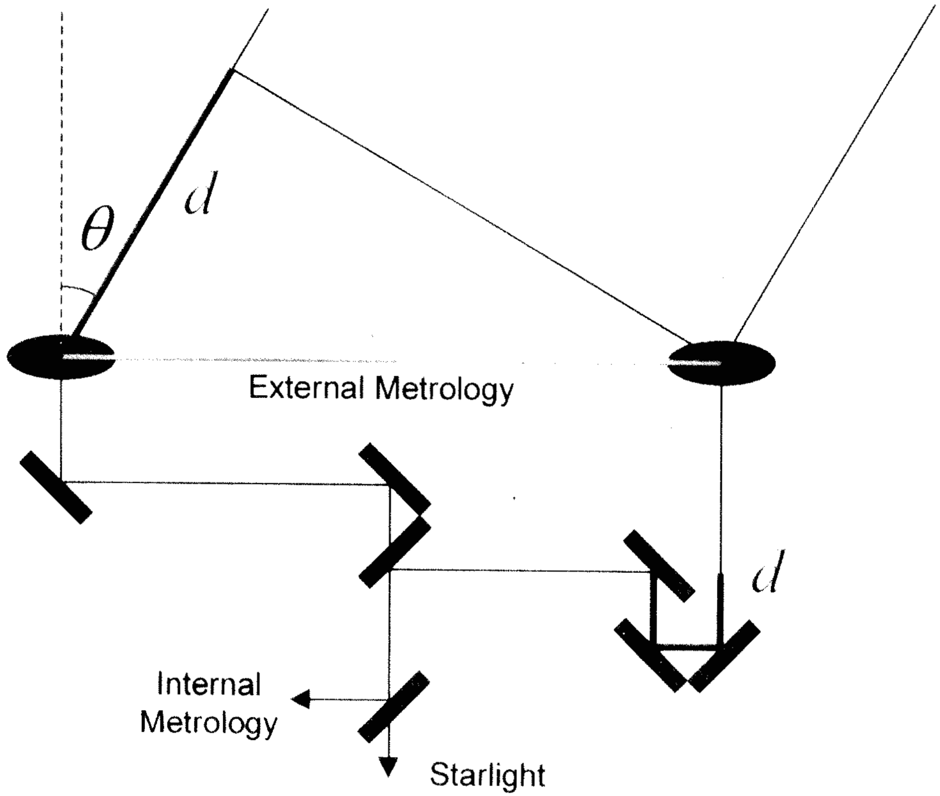


Palomar Testbed Interferometer



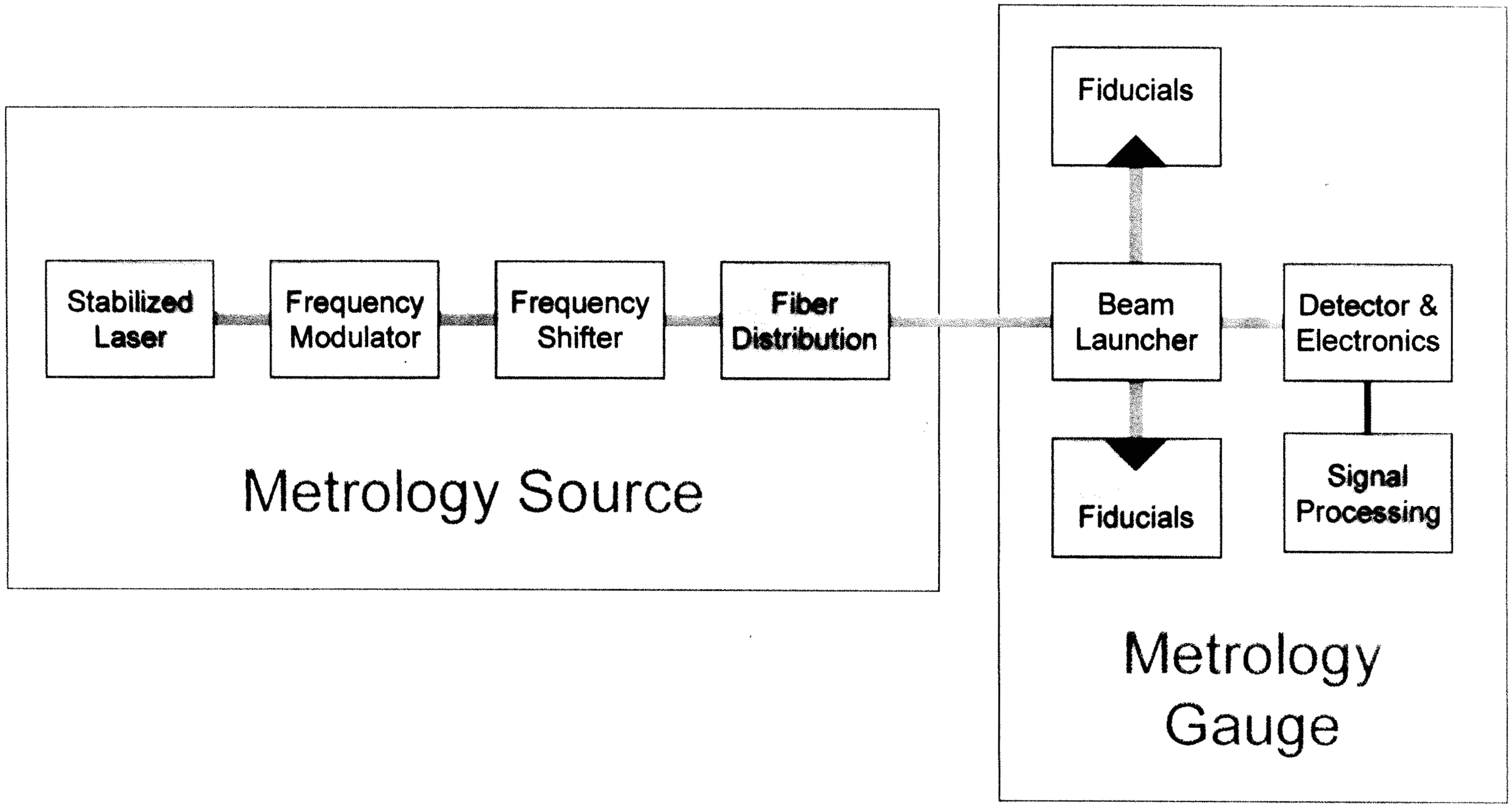
What Does the Metrology Subsystem Measure?

- Two most critical parameters for astrometry
  - Delay Length: Internal Metrology



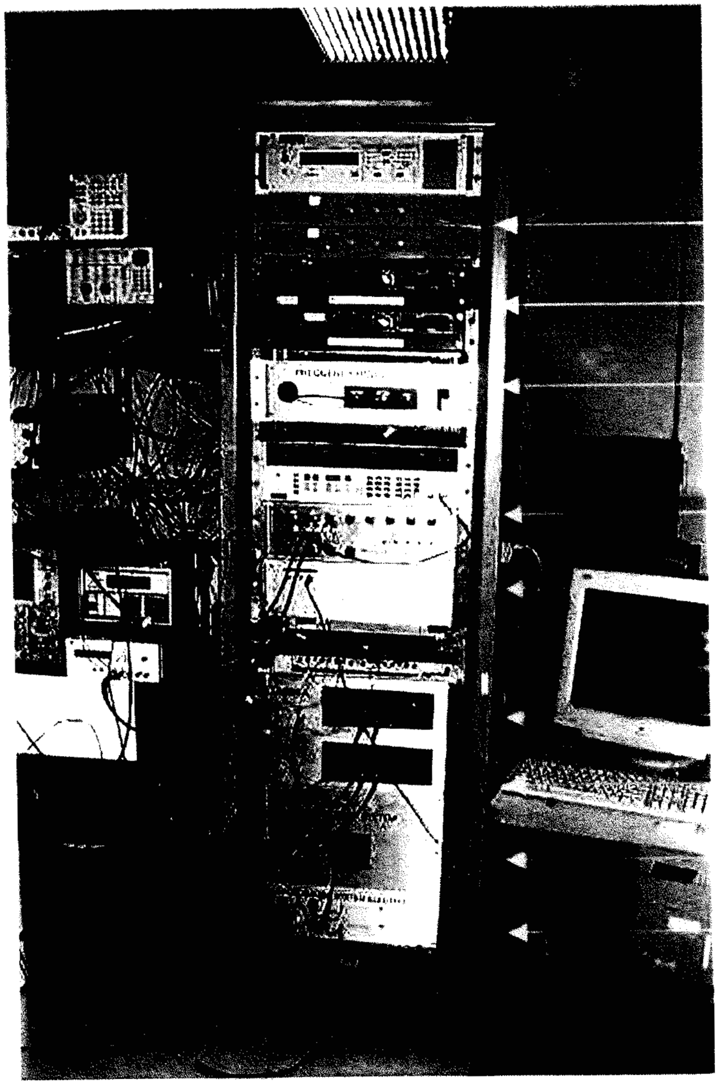
$$\cdot \sin\theta = d$$

Metrology Subsystem Block Diagram



Metrology Source Breadboard Delivered to MAM

(Serge Dubovitsky)



AOFM Digital Drivers

AOFM RF Synthesizers

Acousto Optic Frequency Modulator (AOFM)

AO Frequency Shifter Electronics

AO Frequency Shifter Optics

"Hot" Laser Controller

"Cold" Laser Controller

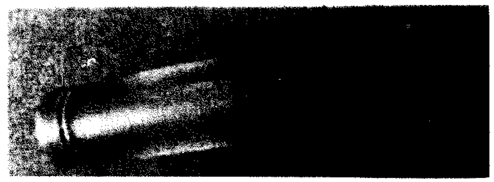
Laser Stabilization Optics

Laser Stabilization Electronics

Stabilized Laser Sub-subsystem

- 1.319 μm Nd:YAG with 350 mW cw output
  - Diode-pumped Nd:YAG Non-Planar Ring Oscillator(NPRO) laser
  - Vendor: Lightwave Electronics

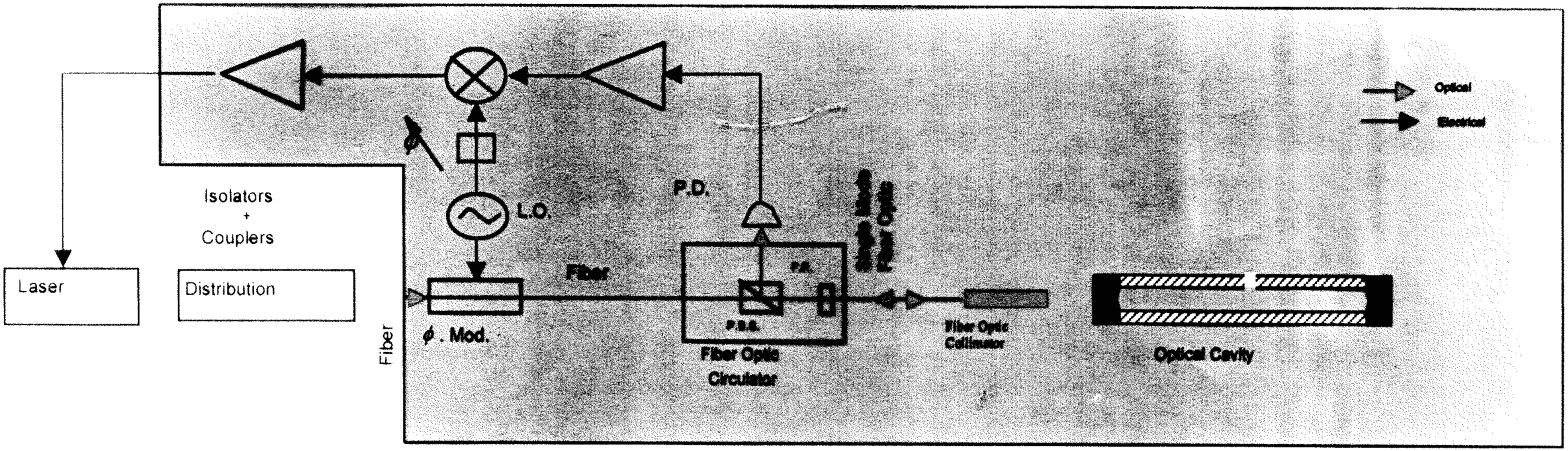
- Laser is mode-locked to 3 cm ULE cavity, ~ 10 μK/sec



- Frequency stability requirement driven by cyclic avg.
  - 450 Hz/sqrt(Hz) for 10 - 1000 Hz
- Laser linewidth 5 kHz => 60 km coherence length

Locking the Laser to the Cavity

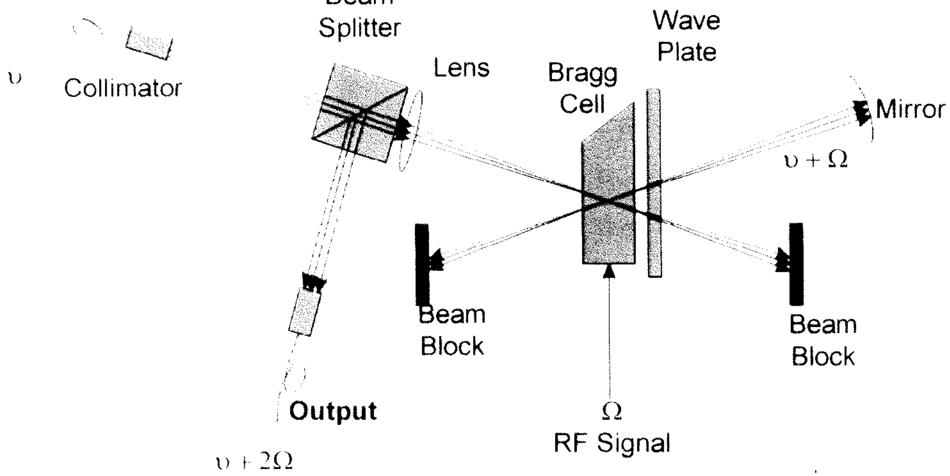
(David Seidel)

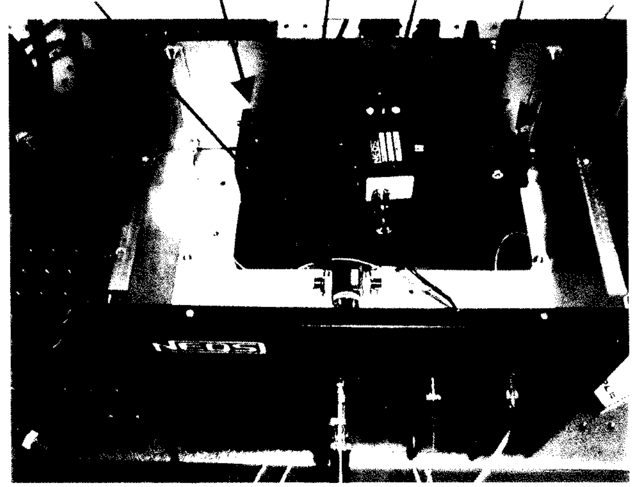


- Use Pound-Drever-Hall Stabilization scheme
  - Easy to acquire lock
  - Easy to reset if necessary
  - Uses integrated optical components
  - Capable of high bandwidth

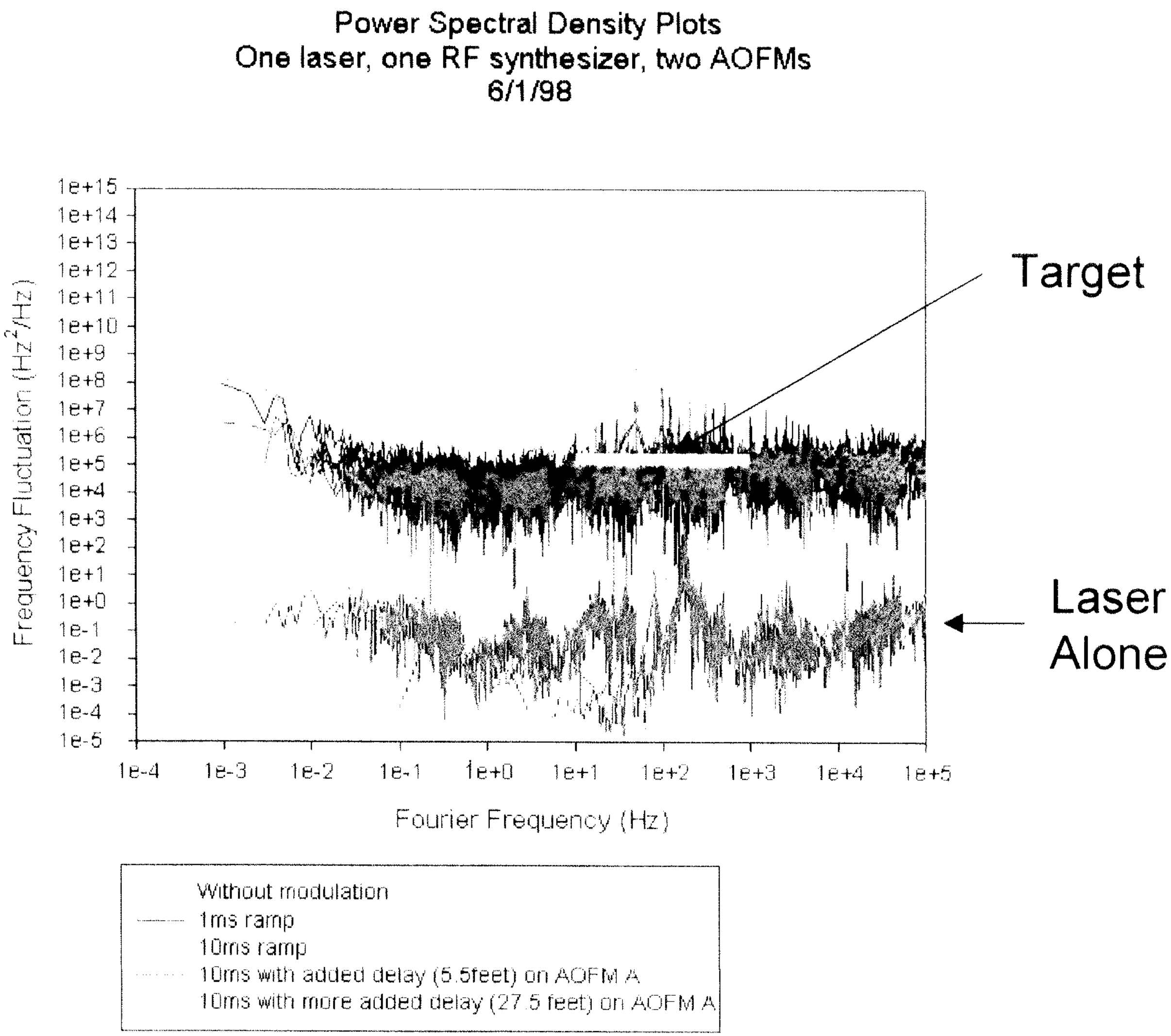
Bulk Acousto-Optic Frequency Modulator

(Duncan Liu)

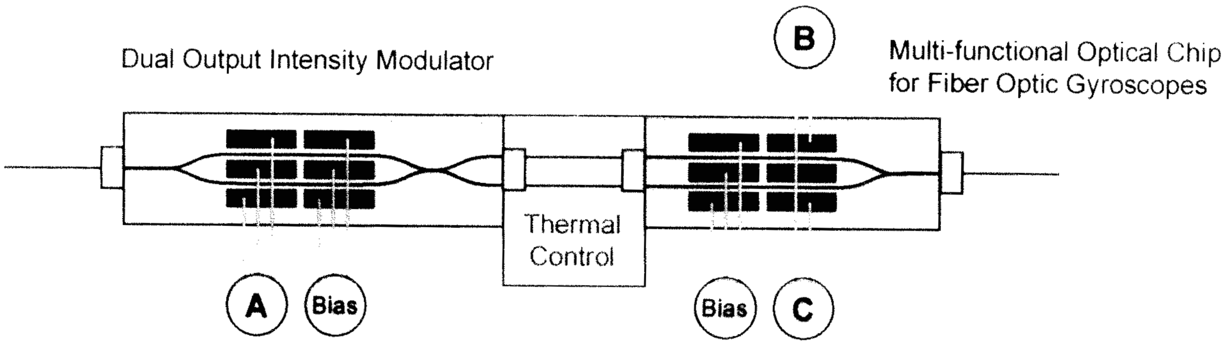




Bulk AO Frequency Shifter Results



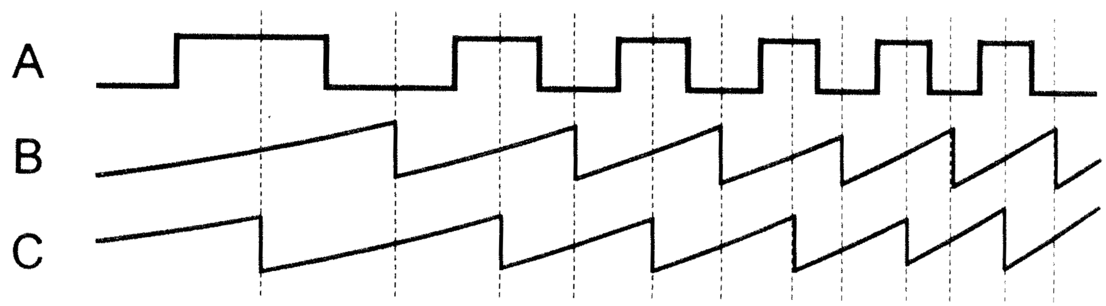
Integrated Optic Frequency Modulator
(Double Serrodyne)



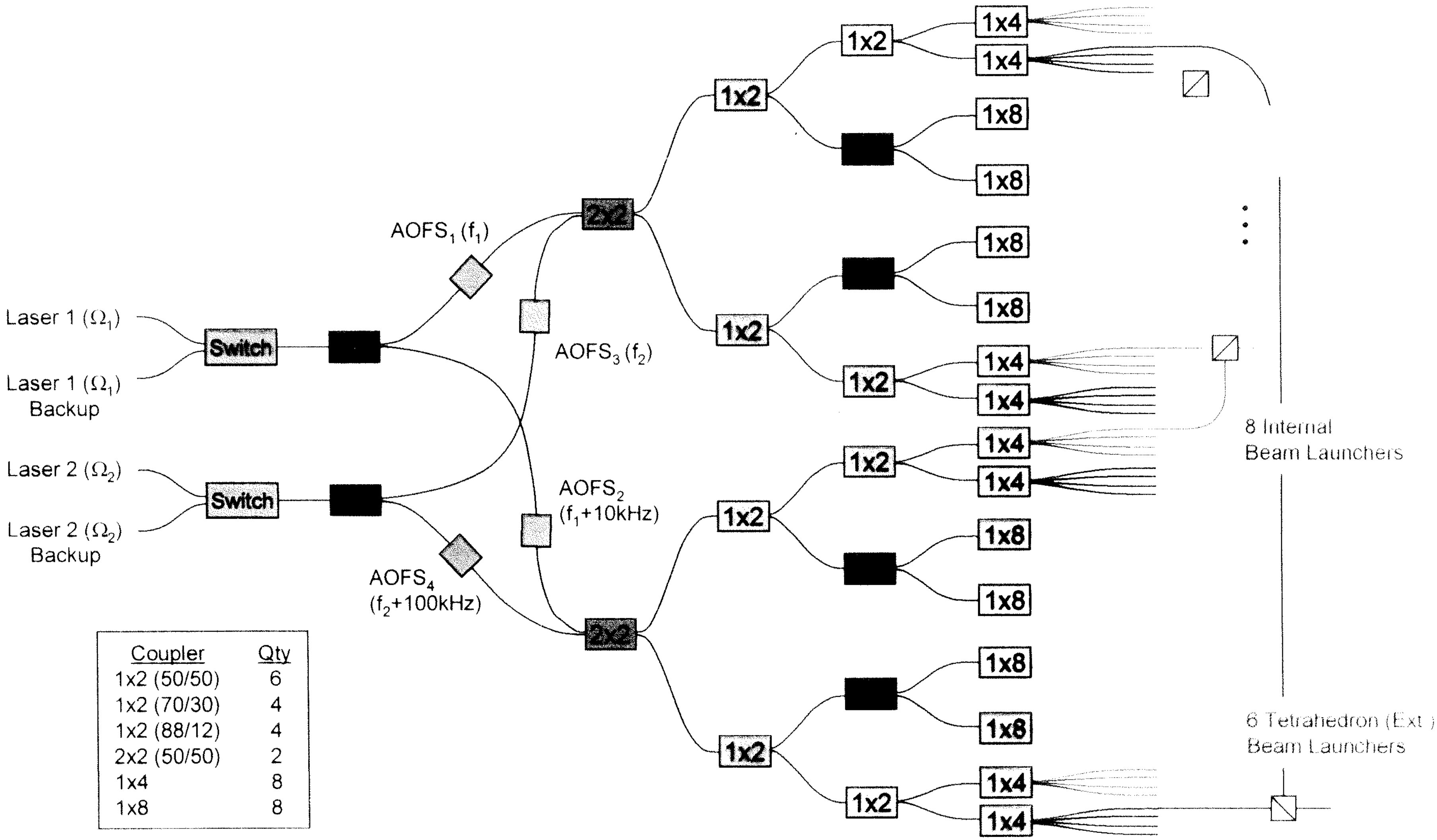
Linear Sweep of Frequency = 10 MHz to 100 MHz

$$\phi = \gamma t^2$$

$$f = \frac{d\phi}{dt} = 2\gamma t$$



Fiberoptic Light Distribution Sub-subsystem

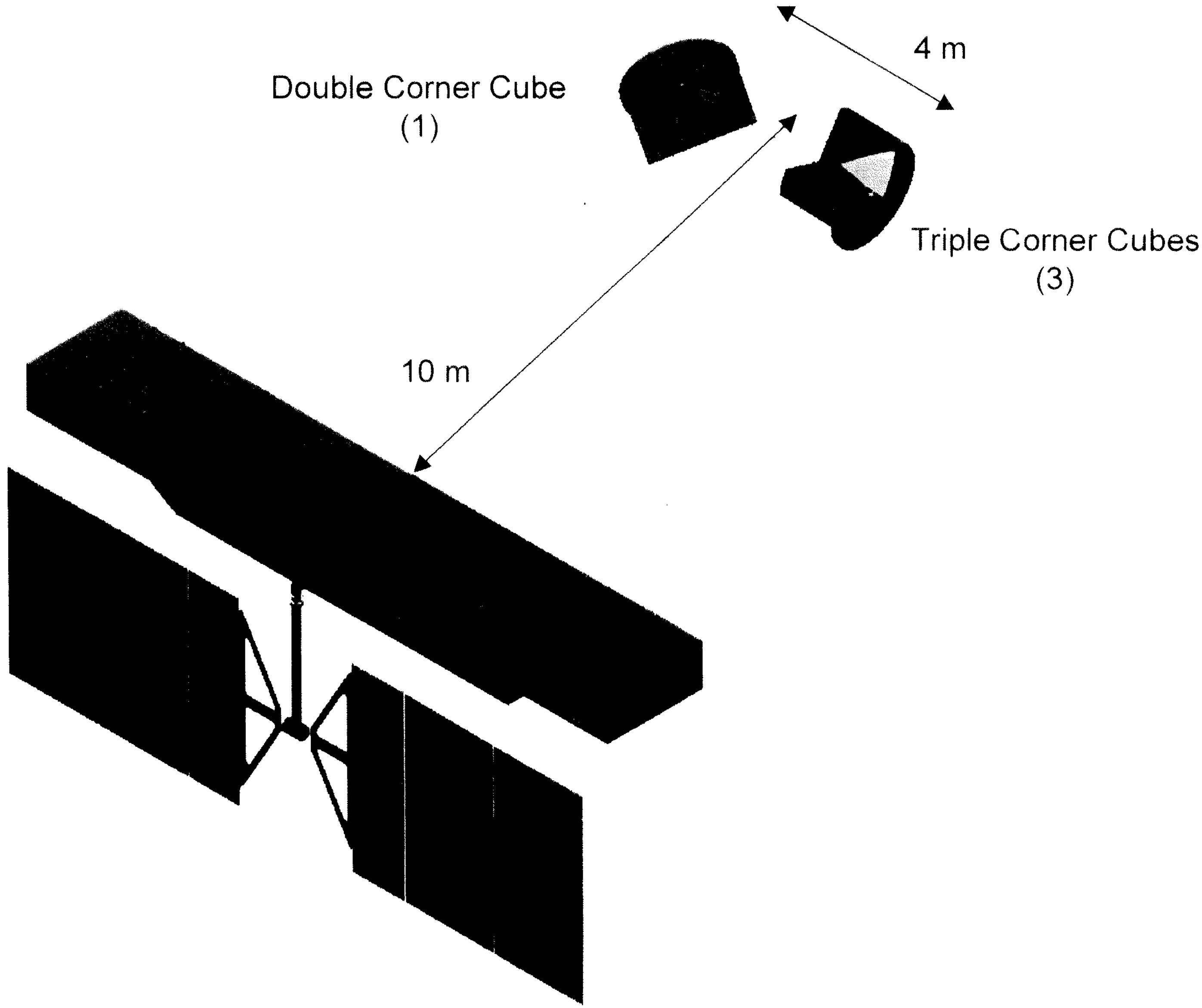


Coupler	Qty
1x2 (50/50)	6
1x2 (70/30)	4
1x2 (88/12)	4
2x2 (50/50)	2
1x4	8
1x8	8

Metrology Beam Radiometry

	External BL	Internal BL	Truss BL	Notes	
Laser Output	1.000	1.000	1.000		
Freq modulator (for Cyclic Avg)	0.316	0.316	0.316	5.00	dB loss
Switch	0.794	0.794	0.794	1.00	dB loss
1x2 coupler	0.462	0.462	0.462	3.35	dB loss/channel
AO Frequency Shifter (Heterodyne)	0.398	0.398	0.398	4.00	dB loss
2x2 coupler	0.462	0.462	0.462	3.35	dB loss/channel
1x2 coupler (power equalizer)	0.277	0.646	0.277	0.70	for internal BL, 0.35 dB excess loss
1x2 coupler (50/50)	0.462			3.35	dB loss/channel
1x2 coupler (power equalizer)		0.812	0.111	0.88	for internal BL, 0.35 dB excess loss
1x8 coupler	0.074			11.30	dB loss/channel (1 dB uniform)
1x4 coupler		0.162	0.162	7.90	dB loss/channel (0.8 dB uniform)
Fiber splices	0.933	0.933	0.933	0.30	dB loss for 6 splices
BL Telescope	0.990	0.990	0.990		
BL PBS	0.950	0.950	0.950		
Ref BS	0.900	0.900	0.900		
BL PBS/QWP	0.950	0.950	0.950		
CC mirrors	0.886	0.886	0.886	0.98	Reflectivity, 3 mirrors/CC, 2 CC
Folding mirrors		0.568		0.98	Reflectivity, 14 mirrors
Beam Comb. BS		0.203			
Atherm PBS	0.950	0.950	0.950		
Polarizer	0.500	0.500	0.500		
Lens	0.990	0.990	0.990		
Detector	0.900	0.900	0.900		Fresnel reflection loss
Diffraction Loss	0.500	0.500	0.950		
Fringe Visibility	0.600	0.600	0.600		
Total Fractional Thru-put	1.71E-05	1.76E-05	1.70E-05		
Total Power Throughput (μW)	**1.712**	**1.765**	**1.704**	**100.00**	**mW laser per arm**

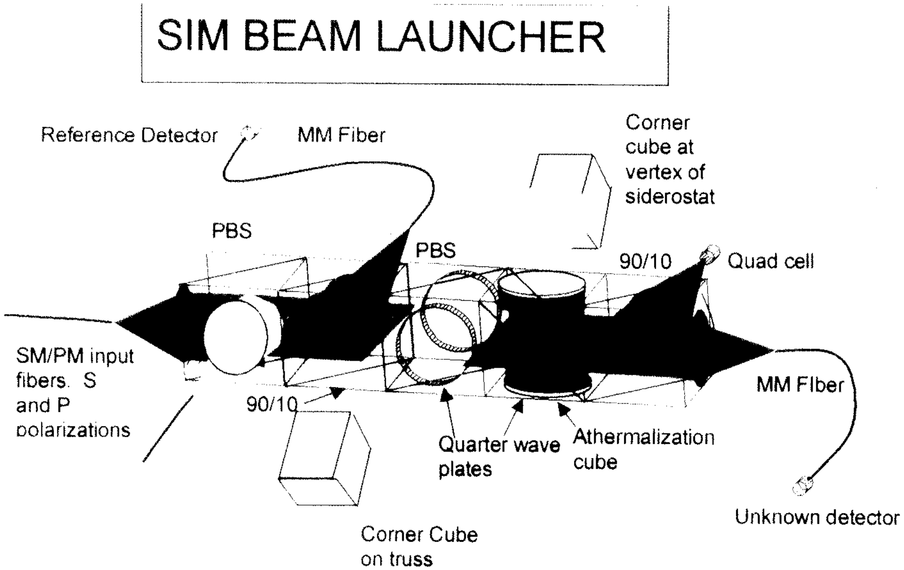
External Metrology Truss



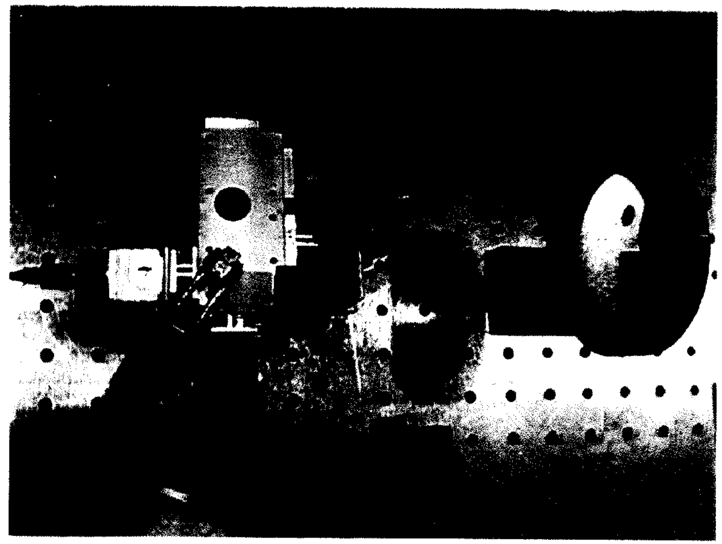
Beam Launchers

- Beam launchers inject a laser beam between fiducial points (corner cubes)
  - Measure a reference phase just before injection
  - Measure the phase of the “unknown” optical path
- Each siderostat has 4 launchers in a “cluster” pointed at the corners of the metrology tetrahedron.
- 32 External metrology gauges
  - Buried in the bay
    - No stray light problem
    - Thermal stability
- 8 Internal metrology metrology gauges
- 6 Tetrahedron gauges to measure corner to corner
- Total count: 8*4 + 6 (external) + 8 (internal) = 46

"Original" Beam Launcher



Athermalized Design



Built Beam Launcher
w/o Athermalized Cube

Beam Launcher Thermal Requirements

- Considering OPD requirement of 20 pm
- Athermalized (original) design:
  - dn/dT = 5e-6
  - delta thickness = 10 microns (cube size difference)
  - *Temperature stability req. for overall temperature is 0.4 K*
  - Also worry about gradient between cubes
    - cube size = 1 cm
    - *Maximum gradient < 0.4 mK across 1 cm*
- Non-athermalized design: overall stability 0.40mK
- Factor of 5 relaxation possible using FK51
- Preliminary data show worse than expected temperature dependence

Metrology Error Budget

(Mike Margulis)

Parameter	Requirement
Metrology requirements	
- Beam launcher thermal effects	10 pm/hour (e.g. CTE=3e-8/K & deltaT=11mK for 3 cm size)
	2 pm/5 min (e.g. CTE=3e-8/K & deltaT= 2mK for 3 cm size)
- Cyclic averaging performance	5 pm cyclic averaging residual error
- Pointing dither on corner cubes	5 pm (e.g. 65 mas/1 kHz sample pointing; 1.6 pm/um)
- Electronics noise and SNR	1 pm (e.g. 5 pm/sqrt(Hz) gauge; >30 sec integration)
- Metrology frequency stability	1 pm (e.g. 25 kHz/s frequency stability; 1 msec sampling)
- Corner cube beam walk	55 pm/15 deg (e.g. 0.25mm beamwalk on CC; cal. by 12.5)
- Metrology slew (diffraction)	130 nm/15 deg slew; factor of 3000 calibration
	9 nm/1 deg slew; factor of 3000 calibration
- Vertex alignment on siderostat	CC vertex to siderostat surface distance: 1 nm knowledge
	CC vertex to siderostat surface distance: 1 um control
	Knowledge of siderostat slew angle: 1 urad
- Vertex alignment on tetrahedron	3 pm (e.g. 2 mm control/knowledge of CC vertex alignment
	& 25 urad knowledge of CC slew error)
- Absolute metrology	13 pm (e.g. 3 um length knowledge; 10 um length control)

Beam Launcher Dithering

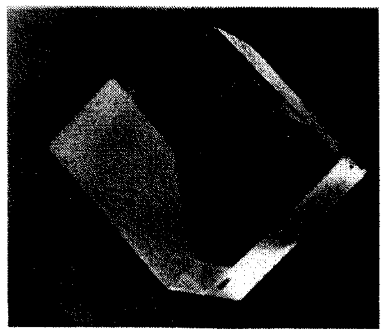
- Pointing the laser beam away from the CC vertex results in a cos θ error.
  - 100 microns from vertex is a 0.5 nm optical path error.
  - Calibrated corner cube surface profile
    - The profile shows OPD vs. pointing error
  - Or use better surface optics (λ/300 - λ /1000)
  - Dither mechanism corrects pointing to null position
    - Phase meter detects for the longest distance
- Current design uses 2-axis PZT for dithering
- Potential use of liquid crystal device
  - Current LC device is 1 axis, 2-3 Hz.
  - 2-axis 10-100 Hz under development (SBIR)
  - May be difficult to make it flight-ready

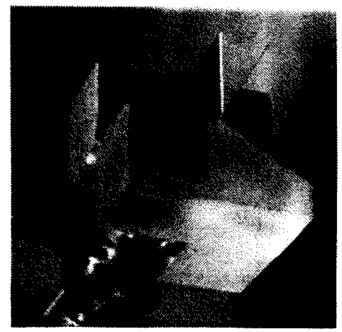
Fiducials: Corner Cubes

- Single corner cube on siderostat
  - Corner cube flatness $\lambda/300$ - l/1000
  - 1 nm co-alignment knowledge
- Triple corner cube on tetrahedron truss
  - 1 C.C. face for all siderostats
  - 2 C.C. face for other vertices of the truss
  - Significantly looser requirement for tetrahedron TCC, $\lambda/20$ rms surface
    - TCC does not move much in the truss
    - 1 nm path error in the tetrahedron => 0.03 nm contribution to astrometric error budget (preliminary result)

Fiducials: Tetrahedron Corner Cubes

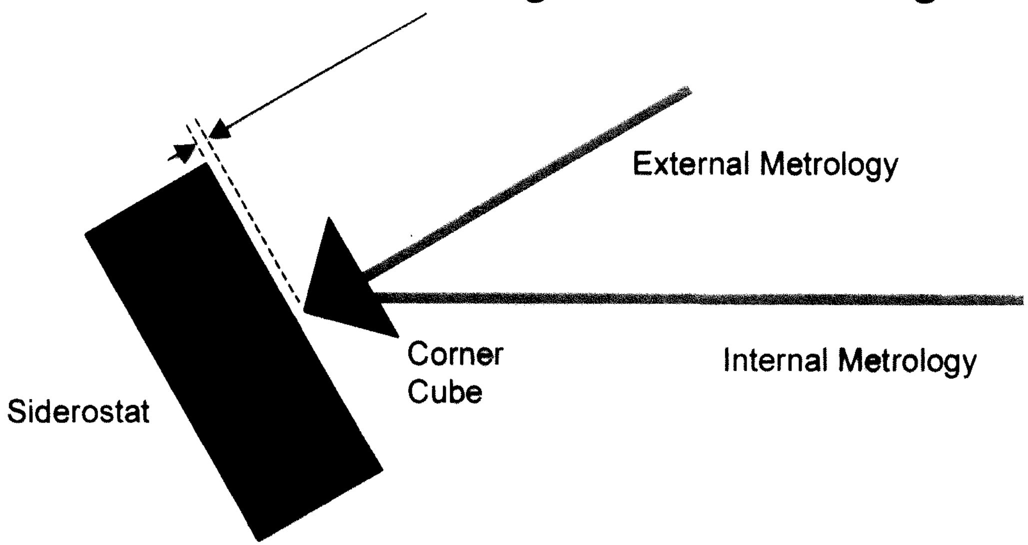
- Tetrahedron has 3 triple- and 1 double-corner cubes
  - 1 C.C. face for all siderostats
  - 2 C.C. face for other vertices of the truss
  - Significantly looser requirement for tetrahedron CCs
    - Corner cubes do not move much in the truss
    - $\lambda/20$ rms surface
- Status: have built one prototype, three more being built for MAM testbed
  - vertex co-location to 2 microns
  - Surface: 0.1 - 0.2 waves p-v (d=1 cm) in prototype limited by edge roll-off and face orthogonality.





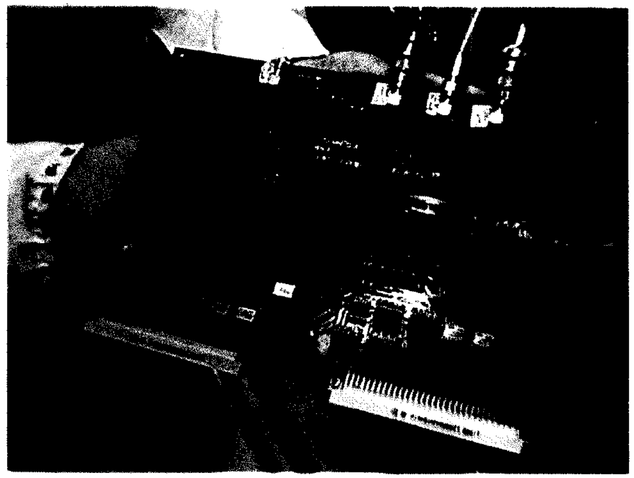
Siderostat-Mounted Corner Cubes

- Siderostat-mounted corner cubes are fiducials for both internal and external metrology beams
- Single corner cube on siderostat
- Tight tolerance
  - 7.5 deg. Siderostat mirror rotation
  - Corner cube flatness λ/300 - l/1000
  - 1 nm vertex to mirror co-alignment knowledge



Digital Phase Meter

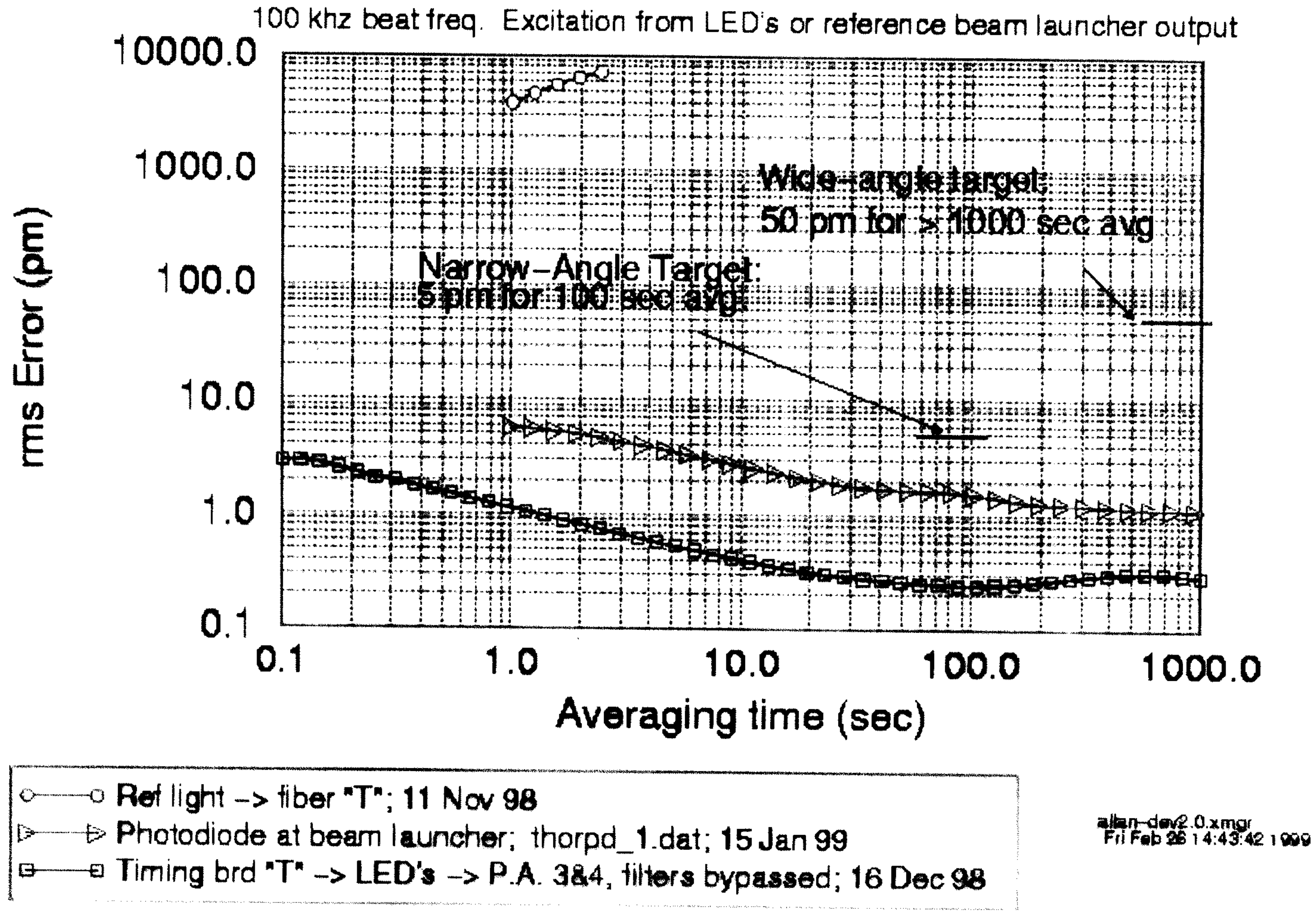
- "Laser card" counts the phase difference between ref-unknown pairs
- It integrates at 1 kHz to perform cyclic averaging.
  - Output: 1 kHz cyclic-averaged phase
- On board computers integrate these signals to a desired lower bandwidth (1 Hz, 100 Hz...) for downlink
- MAM design has 6 pairs per card
- For flight h/w, may need to put one phase meter per card for robustness



Beam Launcher Electronics Test Results

(Robert Spero, Andy Kuhnert, Peter Halverson)

Allan deviation of analog electronics drift and noise



Issues to be Resolved

- Laser source
  - Stability, lifetime
  - Direct modulation via offset laser locking
- Frequency modulators and shifters
  - Linearity, stability, insertion loss
- Metrology gauge
  - Athermalized design validation
  - Validate dithering & cyclic averaging
  - Eliminate cyclic averaging with a low pol. leakage BLs?
  - Corner cube assembly and testing
- Absolute metrology
  - Demonstrate 3 μm absolute met. for 10 m path
  - Hot & cold laser lifetime issues

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